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PRELIMINARY INVESTIGATION OF EFFECT OF HYDROGEN ON STRESS-RUPTURE AND FATIGUE PROPERTIES OF AN IRON-, A NICKEL-, AND A COBALT-BASE ALLOY

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SUMMARY

The effect of hydrogen on the elevated-temperature axial-tensile-fatigue and stress-rupture properties of three high-temperature alloys was investigated. The test temperature for A-286 alloy was 1200° F, while that for Inconel 700 and S-816 was 1500° F. Each alloy was tested at a single mean stress level in axial fatigue (49,500 psi for A-286, 33,000 psi for Inconel 700, and 16,000 psi for S-816) and at a different single stress level in stress rupture (57,000 psi for A-286, 40,000 psi for Inconel 700, and 19,000 psi for S-816). A ratio of the alternating tensile load to mean tensile load of 0.5 was maintained during the fatigue tests. Hollow specimens were used. In one series of tests, dried hydrogen was forced through the specimens, while their exterior surface was exposed to a normal air atmosphere and a heat source. The tests were repeated with dried air as the internal gas.

The average fatigue lives of all the alloys were not significantly decreased as a result of the hydrogen environment compared with the average fatigue lives obtained in the air tests. Comparison of the average stress-rupture lives obtained from hydrogen and air tests with A-286 and Inconel 700 showed no significant differences. S-816, however, provided average stress-rupture lives of 151 and 215 hours for the hydrogen-tested and air-tested specimens, respectively. The difference in lives was statistically significant.

Cracks appeared on both the internal surface (hydrogen side) and the external surface (air side) in the failure area of hydrogen-tested fatigue and stress-rupture specimens. Normally these cracks were not concentrated primarily on one surface in preference to the other. Fatigue failures were generally transgranular in nature, while stress-rupture failures were intergranular for each of the materials investigated, regardless of the internal gas.

INTRODUCTION

The actual and contemplated uses of hydrogen in various aerospace applications has increased the need for learning more about its effect on the mechanical properties of metals. Among the more important aerospace applications in which hydrogen may be used are aircraft turbine engines and the rocket motors of missiles and space vehicles. For example, it has been shown (ref. 1) that additional degrees of freedom in design and operation are possible in aircraft in which the turbine buckets are cooled. Although air is the most common gaseous coolant considered, the excellent heat-transfer properties (high specific heat and thermal conductivity) of hydrogen indicate that it has a considerably greater potential as a turbine-cooling medium. In liquid-propellant rocket motors the use of hydrogen as a fuel affords great promise for producing specific impulse. Thus, the effect of hydrogen on the elevated-temperature mechanical properties (including stress rupture and fatigue) of metals that might be used in such applications becomes of paramount importance to designers of aerospace vehicles.

Investigations have been conducted with steels, nickel, and nickel-base alloys, as well as refractory metals such as columbium (refs. 2 to 9), to study the effects of a gaseous-hydrogen environment on various mechanical properties of these materials. The mechanical properties considered were tensile strength, elongation, reduction of area, stress-rupture life, and creep rate. These studies were made in many different ways and under a wide variety of test conditions and generally showed that hydrogen adversely affected one or more of these properties for all materials considered.

For example, reference 4 indicates that tubular specimens of low- and medium-alloy steels (0.12 to 0.25 percent carbon, 0.34 to 1.5 percent silicon, 0.33 to 0.50 percent manganese, 1.14 to 2.98 percent chromium, 0.20 to 0.50 percent molybdenum, 0 to 0.70 percent vanadium, 0 to 0.40 percent tungsten, and 0 to 0.1 percent titanium) pressurized with hydrogen demonstrated up to 40 percent lower rupture strength (at a test temperature of 1100° F and for times of 1000 and 10,000 hr) than specimens pressurized with nitrogen. In these tests, the internal gas pressure, which was maintained constant, provided the loading force. A high-alloy steel (0.12 percent carbon, 0.74 percent silicon, 1.15 percent manganese, 17.25 percent chromium, 10.35 percent nickel, and 0.45 percent titanium) also showed reductions in rupture strength up to 20 percent at these same test conditions. Detrimental effects were also observed with nickel and nickel-base alloys (refs. 5 to 8). After exposure to hydrogen under 2000 atmospheres pressure at a temperature of 475° C for periods ranging from 3 hours to 4 weeks, five nickel-base alloys exhibited embrittlement in room-temperature tensile tests as well as in bend tests at room temperature and at 475° C (ref. 5). The investigators of reference 5 determined the degree of embrittlement by visual examination of failed specimens. Studies of the creep rate of pure "A" nickel at 1380° F also showed a hydrogen environment to be detrimental (ref. 6). The creep rate was decreased by more than 50 percent when the atmospheric environment of the test was changed from hydrogen to air. Columbium was observed to exhibit a 72-percent decrease in room-temperature elongation after exposure to hydrogen at 400° C for 3 hours (ref. 9).

Various postulates have been made to describe the mechanisms that occur when metals are exposed to a hydrogen atmosphere. In reference 2 it is suggested that monatomic hydrogen can diffuse into the metal and recombine to form molecular hydrogen in grain boundaries and voids, thereby generating high internal pressures that cause a brittle type of failure. Reference 4 suggests that in metals containing unstable carbides hydrogen may react with these carbides to form methane-gas molecules thereby weakening the microstructure. In the refractory metal, columbium embrittlement has been attributed primarily to hydride formation (ref. 9).

Although considerable background is available regarding the effect of hydrogen on various mechanical properties of metals, additional data are required to determine its effect on the strength of specific classes of materials exposed in a manner similar to that encountered in aerospace applications. An investigation was therefore initiated at the NASA Lewis Research Center to indicate possible effects of hydrogen on elevated-temperature axial-tensile-fatigue and stress-rupture properties of some heat-resistant alloys. Fatigue and stress-rupture tests were conducted with externally heated hollow heat-resistant alloy specimens through which gaseous hydrogen was passed under a pressure of 500 pounds per square inch. This pressure was considered to be representative of that likely to be encountered in a cooled turbine-bucket application. The investigation was repeated with air as the internal gas at the same pressure to provide comparative data. The alloys selected were an iron-base alloy (A-286), a cobalt-base alloy (S-816), and a nickel-base alloy (Inconel 700). The A-286 alloy tests were conducted at a specimen temperature of 1200° F. Both the S-816 and Inconel 700 alloy tests were made at a specimen temperature of 1500° F. The mean stress levels utilized for the fatigue tests were 49,500, 33,000, and 16,000 pounds per square inch for A-286, Inconel 700, and S-816, respectively, while stress levels for the stress-rupture tests were 57,000, 40,000, and 19,000 pounds per square inch, respectively. Typical specimens were studied metallographically at completion of the tests.

MATERIALS, APPARATUS, AND PROCEDURE

Materials Studied

Three materials, an iron-base alloy (A-286), a nickel-base alloy (Inconel 700), and a cobalt-base alloy (S-816), were selected for this investigation. These alloys are of the precipitation-hardening type, although they differ with respect to the precipitating phases that contribute to their strength at elevated temperatures. For example, in A-286, precipitation hardening occurs through the formation of a submicroscopic coherent precipitate, the equilibrium phase of which is Ni_3Ti (ref. 10). In Inconel 700, which contains relatively large percentages of aluminum and titanium, precipitation hardening probably occurs through the formation of the $Ni_3(Al,Ti)$ intermetallic compound of the gamma-prime phase (ref. 11). S-816 owes most of its strength to the precipitation of carbides, although its strength can also be enhanced through cold work by forging. The chemical compositions of the as-received materials are listed in table I.

The material was received as 1-inch-diameter bar stock. The bar stock in each alloy group was from the same original material heat. The as-received stock of each alloy was cut into $2\frac{3}{4}$-inch lengths, which were given the standard heat treatments listed in table II.

Test Specimens

A tubular-type test specimen (fig. 1) was chosen in order to simulate a turbine bucket cooling configuration in which gaseous hydrogen would flow under pressure through drilled cooling passages in the bucket while its external surface was exposed to a heat source. In an effort to minimize any detrimental effects of surface condition on fatigue life, the external surface of the specimen was ground in an axial direction to a finish of 16 microinches. The internal surface was honed to an 8-microinch finish. External threads were provided for gripping. The type of specimens used was identical for both fatigue and stress-rupture tests.

Apparatus and Instrumentation

Figure 2 illustrates the fatigue test installation. The major components include a direct-tensile-stress-fatigue machine, a resistance-heated tube furnace, a tubular-type test specimen, and a gas supply train. Mean tensile loads were applied by a hydraulic piston, which also compensated for specimen elongation during test. Alternating loads were applied by a calibrated cam-operated lever arm at a frequency of 1970 cycles per minute. This frequency is a design characteristic of the machine. The test was interrupted and loads were checked at regular intervals by utilizing a dial indicator mounted on a deflection bar to measure the amount of bending in the lever arm. Universal joints were used on the loading assembly to minimize bending stresses. The gas (hydrogen or air) was introduced and removed through 1/4-inch stainless-steel tubes heliarc welded to each end of the specimen. Hollow grips were slipped over these and threaded to the specimen ends. Three thermocouples were attached to each specimen, one at the center of the test section and one on each shoulder. The central thermocouple was wired to the test section and was used to control the specimen temperature, which was maintained within $\pm 10^{\circ}$ F of that desired. The shoulder thermocouples were spotwelded in place and were used to measure the temperature distribution along the length of the specimen.

Hydrogen gas (99 percent purity) and air were supplied from pressurized cylinders. A regenerative-type dryer, utilizing activated alumina, was employed in the inlet line between the gas supply and the test specimen. Before beginning each test, the dewpoint of the gas (hydrogen or air) was checked after it passed through the dryer. Test operation was initiated only when the dewpoint was -70° C or lower. The internal gas flow rate (either hydrogen or air), measured at room temperature and pressure, was 2 cubic feet per hour. The pressure inside the specimen during the test was 500 pounds per square inch. A pressure-sensitive switch was utilized to shut off both the gas flow and the timer, which logged specimen life, at the instant of specimen failure. The time of failure was defined as the moment the specimen broke or developed a crack large enough to cause a gas leak and pressure drop in the system of approximately 50 pounds per square inch.

A standard stress-rupture machine was used for the stress-rupture tests. The specimens were supplied with gas and were heated in the same manner as in the fatigue tests. Failure was defined in the same manner as it was for the fatigue tests.

Test Procedure

Fatigue tests. - The specimens were subjected to a tensile load that was alternately decreased and increased through the action of the cam-operated lever arm. The ratio of the amplitude of the alternating stress to mean tensile stress, referred to as the "A" factor, was maintained at 0.5 for the alloys investigated. The applied mean tensile stress was set at 49,500 pounds per square inch for A-286, 33,000 pounds per square inch for Inconel 700, and 16,000 pounds per square inch for S-816. These stresses were selected to limit the test length to times considerably below 1000 hours. Specimen test temperatures were maintained at 1200° F for A-286, and 1500° F for both Inconel 700 and S-816. Five to seven specimens of each alloy were investigated with air flowing through the specimens. Five specimens of Inconel 700, five of S-816, and two of A-286 were investigated with hydrogen as the internal gas. The number of specimens available (from the same heat) after initial checkout runs prevented additional tests with the A-286 alloy.

Stress-rupture tests. - In the stress-rupture investigation the applied stresses were chosen to provide test times generally comparable to those of the fatigue study. The stresses applied were 57,000 pounds per square inch for A-286, 40,000 pounds per square inch for Inconel 700, and 19,000 pounds per square inch for S-816. Specimen temperature was again maintained at 1200° F for A-286 alloy and 1500° F for both Inconel 700 and S-816 alloys. Four specimens of each alloy were investigated with air as the internal gas. Five or six specimens of each alloy were investigated with hydrogen as the internal gas.

Metallographic studies. - Failed specimens of all alloys were examined metallographically to study the fracture mechanism as well as the effect of environment on microstructure. Photomicrographs were taken both away from and in the region of fracture at magnifications of 100 and 500.

RESULTS AND DISCUSSION

The results of fatigue and stress-rupture tests of A-286, Inconel 700, and S-816 alloys with either hydrogen or air as the internal gas are summarized in tables III and IV. These data are also plotted in figures 3 and 4. Photomicrographs of failed specimens are shown in figures 5 to 10.

Fatigue Studies

The average life of each alloy tested with air or hydrogen as the internal gas is given both in cycles and in hours in table III. In this discussion, life is referred to in hours rather than in cycles. The average lives obtained for A-286 were 246 hours (air) against 207 hours (hydrogen); for Inconel 700, 372 hours (air) against 482 hours (hydrogen); and for S-816, 398 hours (air) against 345 hours (hydrogen). A comparison of average-life values for A-286 and S-816 shows slightly longer fatigue lives in tests with an internal air atmosphere than with an internal hydrogen atmosphere. Of course, it should be remembered in making these comparisons of average life that only two specimens of A-286 were available for the hydrogen tests. The test results of the remaining alloy (Inconel 700) indicate an opposite trend; that is, the average life obtained with an internal hydrogen atmosphere is considerably greater than that obtained with an internal air atmosphere. Inspection of a plot of all the fatigue data (fig. 3), however, casts some doubt on the possible significance of these differences in average life. It is apparent from the figure that there is considerable overlap of both the hydrogen and the air data for each alloy, thus making definitive differences in life difficult to ascertain. It should be noted that a rather large amount of scatter is generally obtained in fatigue tests, and the scatter shown in figure 3 is not unique. Standard deviations for each set of data were calculated by the method of reference 12 and are also tabulated in table III. For Inconel 700, the one alloy that showed an appreciable difference in average fatigue lives as obtained in hydrogen and air tests (482 against 372 hr), the calculated standard deviations were particularly large. These large deviations would tend to cast doubt on the significance of the observed differences in average lives.

In order to evaluate the data more effectively, statistical techniques were employed and confidence levels were calculated by using the method described in reference 13. These are also tabulated in table III. A confidence level is intended to show whether or not there is a significant difference between two given sets of data and may be expressed in percentile. In considering the average lives obtained in hydrogen and air tests of these alloys, only calculated confidence levels of 95 percent or greater were judged to be indicative of significant differences in life. In no case was the calculated confidence level as high as 95 percent. Thus, it would appear that no practical significance should be attached to the observed differences between average fatigue lives obtained in hydrogen and air tests for any of the alloys. Based on the preceding considerations, it is reasonable to conclude that hydrogen did not adversely affect the axial fatigue life of any of these alloys under the conditions of this investigation.

Stress-Rupture Studies

The results of the stress-rupture tests are summarized in table IV. Average lives and standard deviations are again tabulated. The average lives obtained for A-286 were 264 hours (air) against 215 hours (hydrogen); for Inconel 700, 209 hours (air) against 206 hours (hydrogen); and for S-816, 215 hours (air) against 151 hours (hydrogen). A comparison of average-life values for A-286 and S-816 shows somewhat longer stress-rupture lives in the air tests than in the hydrogen tests. The average life of Inconel 700, regardless of the internal gas, was virtually the same. Figure 4, however, suggests that only one of the alloys, S-816, demonstrated a marked tendency toward lower life for the hydrogen data. From table IV, it is evident that the standard deviations are also quite low for the S-816 hydrogen and air data, which tends to substantiate this apparent trend. Confidence levels were calculated in the same manner as for the fatigue data and these are also tabulated in table IV. The confidence levels for A-286 and Inconel 700 were less than 95 percent. For S-816, however, the confidence level was greater than 95 percent, which indicates that the observed difference between average life with air and average life with hydrogen is significant for this alloy. Thus, it would appear that the stress-rupture life of only one of the alloys (S-816) was adversely affected by hydrogen.

Metallographic Studies

Photomicrographs of typical failures encountered in both the hydrogen and air fatigue tests for each of the alloys investigated are shown in figure 5. Similarly, photomicrographs of typical failures encountered in stress-rupture tests are shown in figure 6. As shown in these figures, the fatigue-test failures were generally transgranular, and the stress-rupture-test failures were generally intergranular in nature, regardless of the alloy or the gas passed through the specimen. It is evident from figure 6 that many small cracks generally occurred in the area immediately adjacent to the fracture surface in the stress-rupture specimens. Except for S-816 (fig. 5(c)), only a few such small cracks and frequently none at all occurred in the failure area of the fatigue specimens. Macroscopic and microscopic studies of hydrogen-tested fatigue and stress-rupture specimens indicated that these small cracks occurred on both the internal (hydrogen side) and external (air side) surfaces. Normally, they were not concentrated primarily on one surface in preference to the other.

Figure 7 shows photomicrographs of typical tested specimens (fatigue or stress rupture) along the surface exposed to hydrogen. The area chosen was near the point of failure in all cases. Figure 8 presents photomicrographs of additional tested specimens (fatigue or stress rupture) of each alloy along the internal surface, which show areas away from the point of failure. No scale is evident on the surface exposed to hydrogen, however, the microstructure of each of the alloys was affected to varying depths beneath the specimen internal surface. The affected zone was generally continuous through both the cracked and noncracked areas. Some depletion of alloying elements may have occurred in these zones. A-286 shows the narrowest affected zone (figs. 7(a) and and 8(a)). Figure 7(c) indicates that S-816 had the widest affected zone. At a magnification of 500 only the affected zone itself is observable. Its true depth is apparent from the photomicrograph at a magnification of 250. The marked absence of precipitates in the affected zone of the S-816 specimens, both within the grains and in the grain boundary regions, suggests that this material may have been decarburized and considerably weakened by the hydrogen environment. Such a weakening effect may have contributed to the reduction in average stress-rupture life and the apparent lesser reduction in fatigue life observed with this material during the hydrogen tests. It is interesting to note that numerous cracks were observed in this affected zone (fig. 7(c)). Metallographic studies, however, did not indicate that a greater amount of cracking occurred or that fracture was preferentially initiated in these zones compared with the region adjacent to the external specimen surface.

Figure 9 shows typical microstructures along both the internal and the external surfaces of specimens of each alloy after air tests in the areas near the specific points of failure. Figure 10 presents similar photomicrographs of additional specimens of each alloy, which show regions away from the failure area. It is apparent from these figures that, in general, a considerably thicker scale was formed on the external surface exposed to relatively humid air rather than on the internal specimen surface exposed to dried air. This scale extended through both the cracked and uncracked areas. Microscopic examination indicated that considerable oxidation occurred in the cracks that formed near the point of failure of air-tested specimens in all the materials investigated. Oxidation occurred in the cracks that extended from the internal surface as well as those that extended from the external surface. This was most apparent in stress-rupture tested specimens and is best illustrated in figure 9(c). No oxidation occurred in the cracks that extended from the internal surfaces of specimens exposed to hydrogen.

General Considerations

It is interesting to consider some of the results of this investigation in the light of certain concepts proposed by other investigators. References 14 to 16, which deal with the relative effect of vacuum and air environments on the stress-rupture properties of both nickel and nickel-base alloys, indicate that oxidation may have contributed in some cases to the longer lives obtained in the air tests. For example, it was postulated that a material could be strengthened by an adherent oxide film that might form on its surface during exposure at elevated temperatures in air. It was further suggested (refs. 14 and 15) that once a crack has been initiated, an oxide film formed in the tip of the crack could act to reduce the effective stress concentration and thus reduce the crack-propagation rate. Such an oxide formation might even bridge the crack completely, thereby increasing the total load-bearing area. As previously indicated, oxidation was noted both on the surfaces exposed to air and in the cracks that extended from those surfaces to varying degrees in the air-tested specimens of this investigation (figs. 9 and 10). Air-tested S-816 (fig. 9(c)) showed particularly heavy surface scales as well as heavy oxidation in these cracks. It will be recalled that of all the materials investigated, only air-tested S-816 (in stress-rupture) showed any significant indication of improved life over the hydrogen-tested material. It is possible that oxide formation acting in the manner described in references 14 and 15 may have contributed to this improved life.

Of the mechanisms proposed to explain the detrimental effect of hydrogen on many materials, the one dealing with methane formation in the metal (ref. 4) may be particularly pertinent in light of the results obtained herein. Reference 4 suggests that in metals containing unstable carbides, hydrogen may react with such carbides to form methane gas, thereby weakening the microstructure. Carbide strengthening plays a major role in achieving elevated-temperature strength in some superalloy materials. Of the alloys of this investigation, this is particularly true with S-816 in which many carbides are present. It is possible that a reaction of the type suggested in reference 4 may also have contributed to the tendency for S-816 to show lower average stress-rupture and fatigue lives when exposed to hydrogen.

It has also been shown in the literature that other physical properties, in addition to the strength of metals, can be adversely affected by hydrogen. For example, a reduction in ductility without a reduction in strength was observed for certain steels in reference 5. In order to obtain an indication of the effect of hydrogen on the ductility of the materials of the present investigation, measurements of the reduction of area in tested specimens were made. Specimen distortion (lack of concentricity of hollow specimens after test) prevented such measurements from being made in many cases. For those cases in which a satisfactory comparison could be made, no difference in reduction of area was noted between the hydrogen-tested and air-tested specimens for any of the materials. Thus, so far as could be determined, no changes in ductility were caused by the hydrogen environment imposed in these tests with any of the materials investigated herein.

SUMMARY OF RESULTS

An investigation was conducted to determine the effect of hydrogen on the elevated-temperature axial-tensile-fatigue and stress-rupture properties of three high-temperature alloys, A-286, Inconel 700, and S-816. The A-286 alloy was investigated at 1200° F; Inconel 700 and S-816 alloys were investigated at 1500° F. Each alloy was tested at a single mean stress level in fatigue (49,500 psi for A-286, 33,000 psi for Inconel 700, and 16,000 psi for S-816) and a different single stress level in stress rupture (57,000 psi for A-286, 40,000 psi for Inconel 700, and 19,000 psi for S-816). Hollow specimens were employed. In one series of tests gaseous dried hydrogen was forced through the specimens, while their exterior surface was exposed to a normal air atmosphere and a heat source. The tests were repeated with dried air as the internal gas. The following results were obtained:

1. The average fatigue lives of all the alloys were not significantly decreased due to the hydrogen environment as compared with the average fatigue lives obtained in the air tests.

2. Comparison of the average stress-rupture lives obtained from hydrogen and air tests with A-286 and Inconel 700 showed no statistically significant differences. S-816, however, was damaged by hydrogen insofar that average lives of 151 and 215 hours were obtained for the hydrogen and air tests, respectively. This represented a statistically significant difference in life.

3. Cracks appeared on both the internal surface (hydrogen side) and the external surface (air side) in the failure area of hydrogen-tested fatigue and stress-rupture specimens. Normally these cracks were not concentrated primarily on one surface in preference to the other.

4. Fatigue failures were generally transgranular in nature, while stress-rupture failures were intergranular for each material investigated, regardless of whether dried hydrogen or dried air was forced through the test specimens.

5. The microstructures of all the alloys usually revealed depleted zones of varying depths along the surface exposed to hydrogen. These were continuous through both the cracked and noncracked regions.

6. Metallurgical examination revealed a much heavier scale on specimen external surfaces exposed to relatively humid air than that observed on internal surfaces exposed to dried air. This was evident in the region of failure as well as in the regions away from the failure area.

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TABLE I. - CHEMICAL ANALYSIS OF AS-RECEIVED MATERIALS

Alloy	Supplier	Composition, percent by weight																
		Fe	Ni	Co	Cr	Al	Ti	Cu	Mn	W	Si	Mo	Ta	Cb+ Ta	V	P	S	C
[a]A-286	Allegheny-Ludlum Steel Corp.	Bal.	25.70	-----	14.7	0.16	2.12	----	1.28	----	0.47	1.33	----	3.98	0.26	0.015	0.006	0.076
[b]Inconel 700	International Nickel Co.	0.74	45.45	29.21	15.39	3.22	2.29	0.05	0.07	----	0.25	3.17	----	----	----	-----	0.007	0.13
[b]S-816	Allegheny-Ludlum Steel Corp.	3.98	20.19	43.04	19.69	----	----	----	1.10	3.84	0.21	3.55	0.36	----	----	0.016	0.008	0.392

[a]Analysis by independent laboratory.
[b]Vendor's analysis.

TABLE II. - HEAT TREATMENT OF ALLOYS

PRIOR TO MACHINING

Alloy	Heat treatment
A-286	1800° F for 1 hr, oil quench
	1300° F for 16 hr, air cool
Inconel 700	2150° F for 2 hr, air cool
	1600° F for 4 hr, air cool
S-816	2150° F for 1 hr, water quench
	1400° F for 16 hr, air cool

TABLE III. - FATIGUE LIVES OF THREE

HIGH-TEMPERATURE ALLOYS

Alloy	Internal gas	Stress, psi	Temperature, °F	Life: Cycles	Life: Hr	Average life: Cycles	Average life: Hr	Standard deviation, hr	Confidence level, percentile
A-286	Air	49,500	1200	22.6×10^6	191.7	29.1×10^6	246	±39	72
				26.1	220.4				
				31.2	264.2				
				33.6	283.2				
		50,000		32.3	273.1				
	Hydrogen	49,500	1200	16.0×10^6	135.8	24.5×10^6	207	±100	
				33.0	278.2				
Inconel 700	Air	33,000	1500	27.4×10^6	231.9	44.0×10^6	372	±162	84
				32.9	278.0				
				33.1	280.7				
				33.8	286.0				
				47.4	401.6				
				49.2	416.6				
				83.4	705.5				
	Hydrogen	33,000	1500	43.5×10^6	367.6	57.0×10^6	482	±154	
				48.6	411.1				
				49.1	415.5				
				55.2	467.1				
				89.0	750.4				
S-816	Air	15,000	1500	47.8×10^6	404.6	47.1×10^6	398	±150	73
		16,000		31.2	263.8				
				60.1	508.7				
				68.4	578.2				
		17,000		27.5	232.9				
	Hydrogen	16,000	1500	31.0×10^6	262.2	40.8×10^6	345	±60	
				38.2	323.2				
				42.0	357.0				
				42.0	357.1				
				55.8	428.4				

TABLE IV. - STRESS-RUPTURE LIVES OF

THREE HIGH-TEMPERATURE ALLOYS

Alloy	Internal gas	Stress, psi	Temper-ature, °F	Life, hr	Average life, hr	Standard deviation, hr	Confidence level, percentile
A-286	Air	57,000	1200	230.6 253.3 254.2 264.3 316.8	264	±32	83
	Hydrogen	57,000	1200	109.7 125.0 188.9 246.6 280.0 340.0	215	±90	
Inconel 700	Air	40,000	1500	167.3 188.3 196.7 282.0	209	±51	20
	Hydrogen	40,000	1500	154.6 198.3 206.3 207.3 266.2	206	±40	
S-816	Air	19,000	1500	166.6 228.3 232.8 232.8	215	±32	98
	Hydrogen	19,000	1500	120.5 130.6 140.4 161.0 200.2	151	±31	

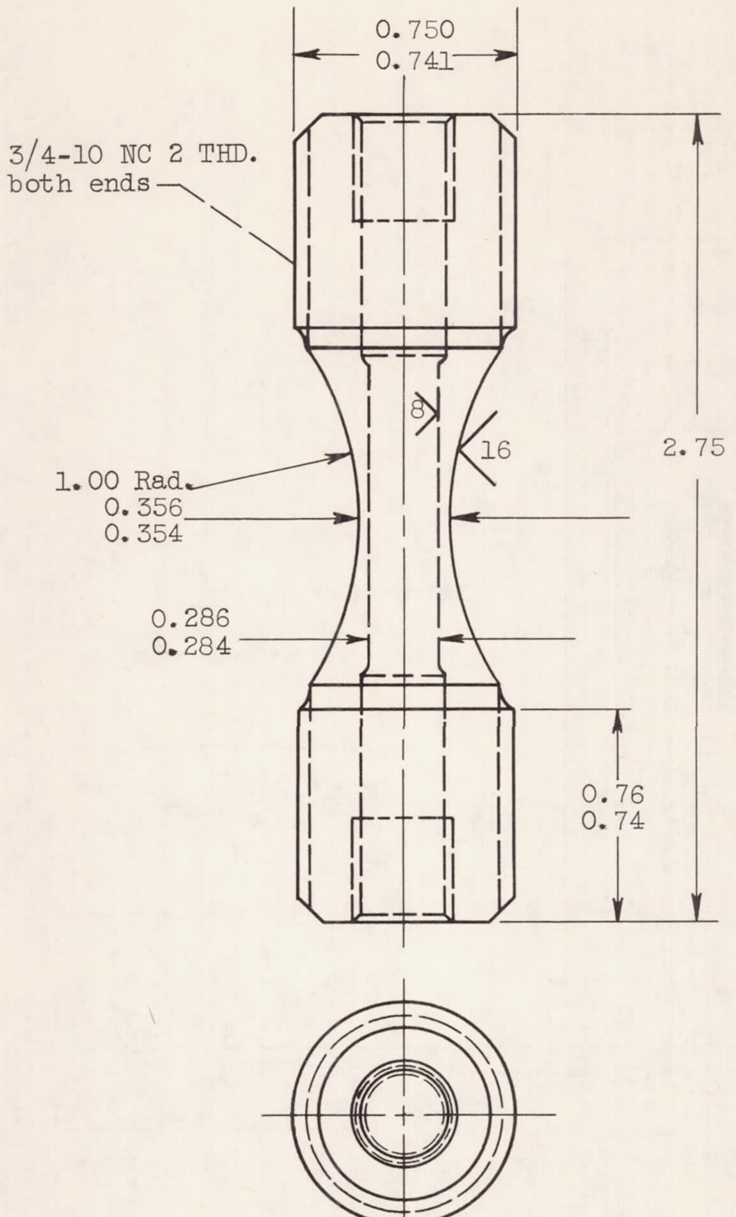


Figure 1. - Hollow fatigue and stress-rupture specimen. (All dimensions in inches.)

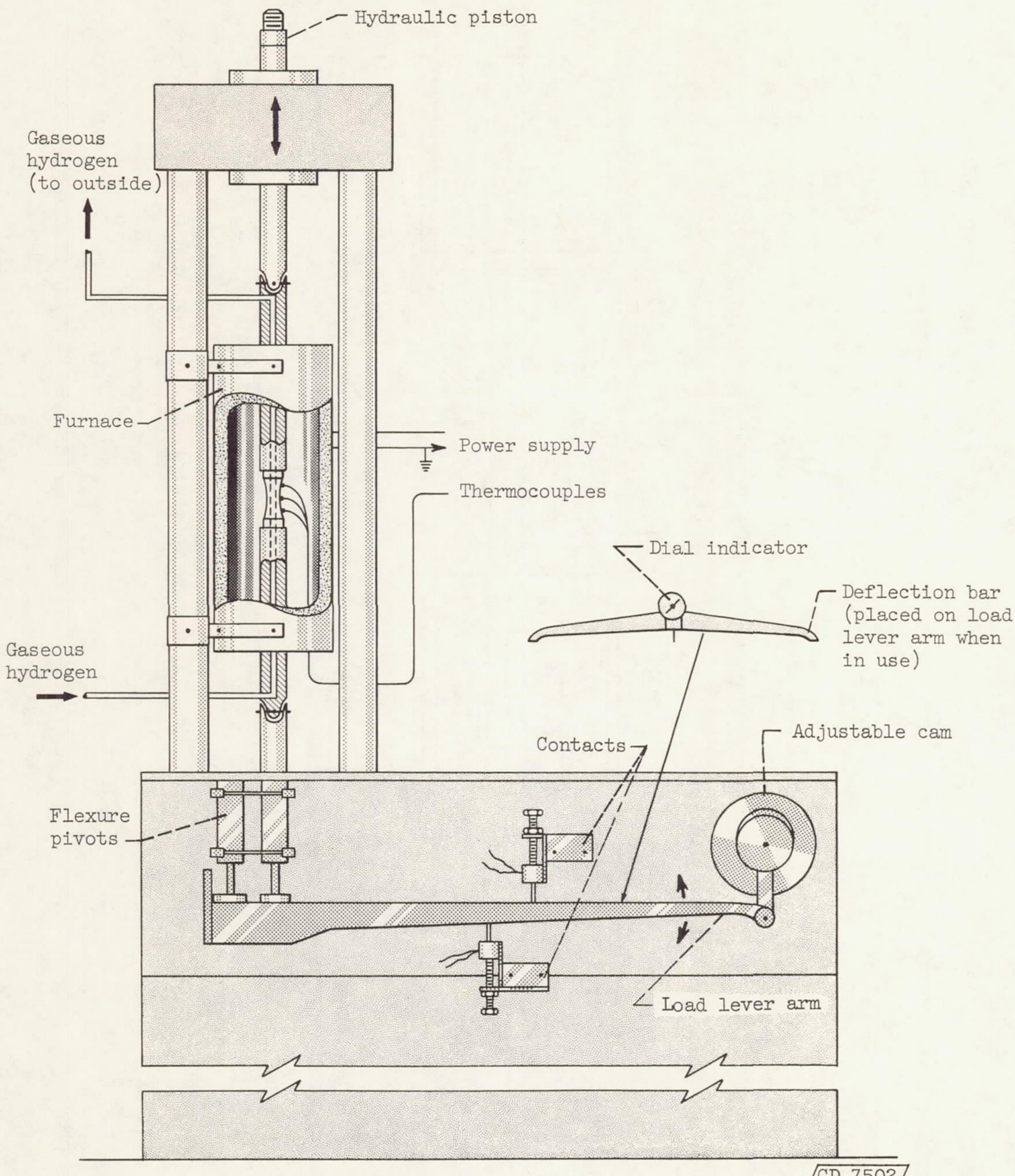


Figure 2. - Fatigue-test apparatus.

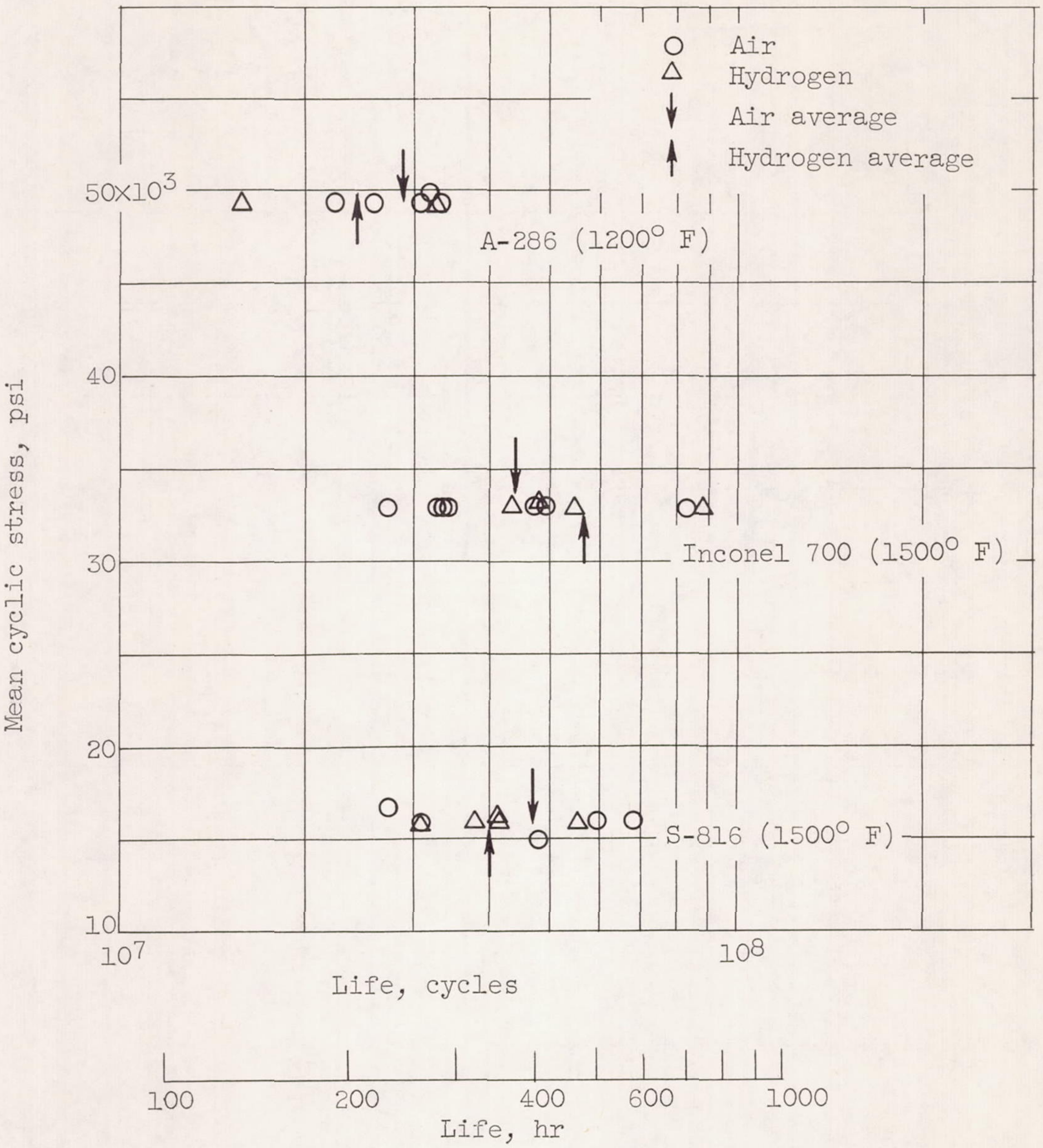


Figure 3. - Comparison of fatigue life of tubular specimens with internal surface exposed to air or hydrogen for three alloys tested at constant stress and temperature.

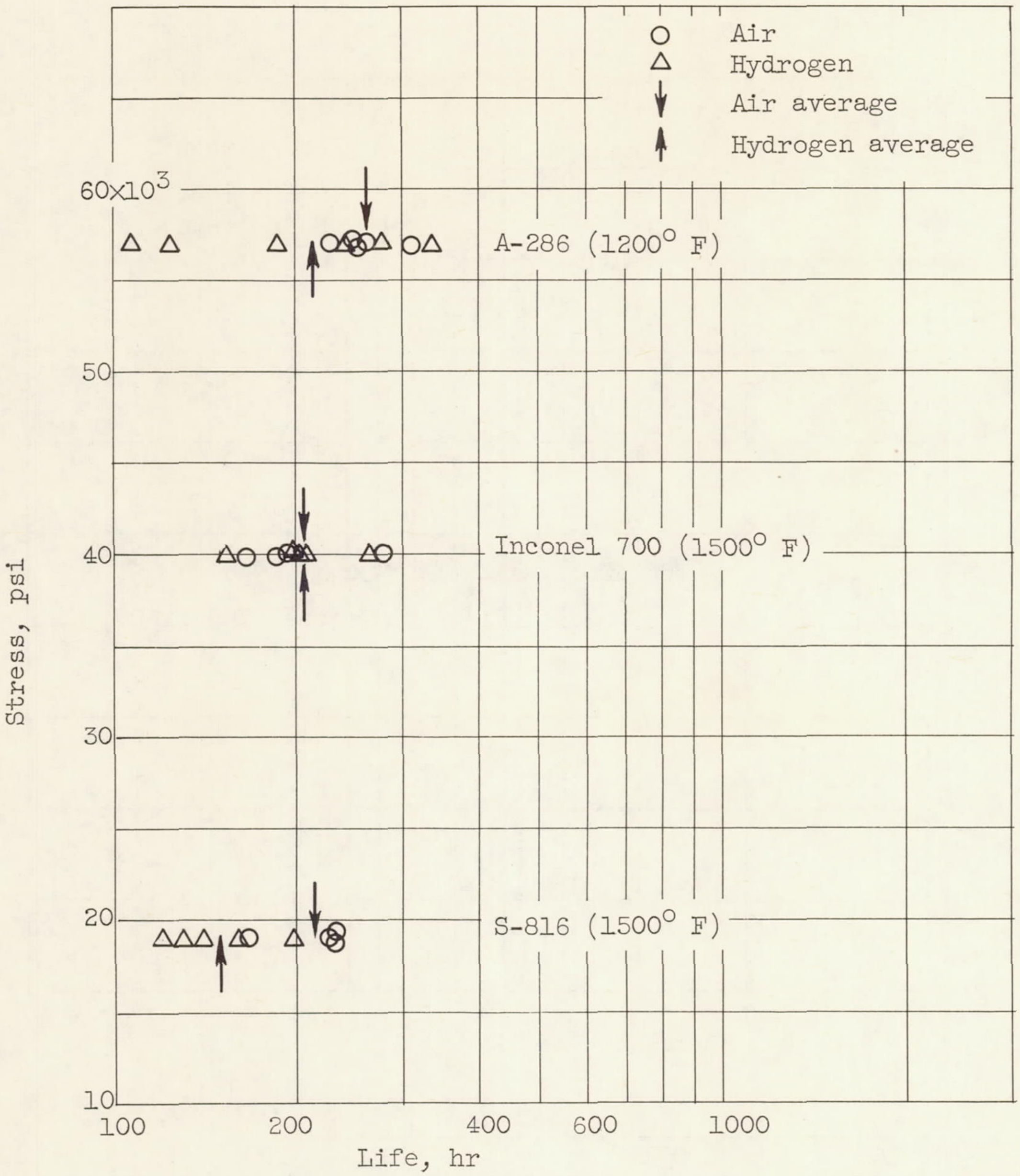
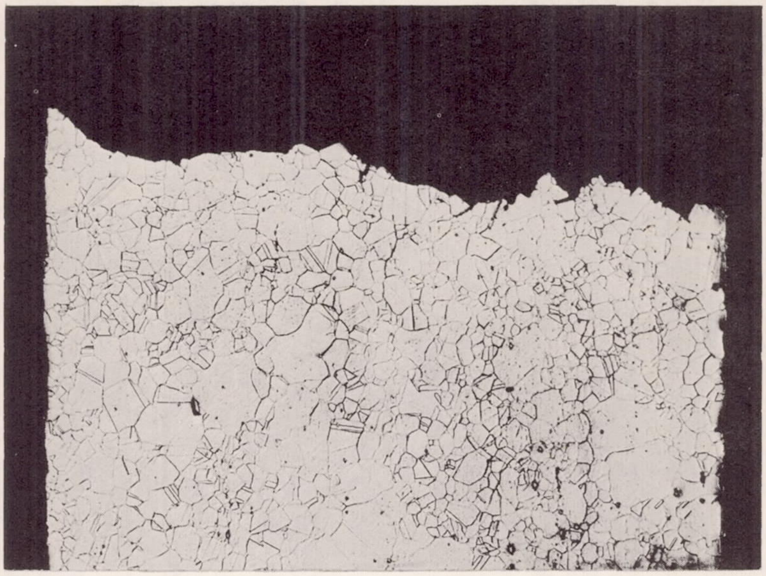


Figure 4. - Comparison of stress-rupture life of tubular specimens with internal surface exposed to air or hyrogen for three alloys tested at constant stress and temperature.

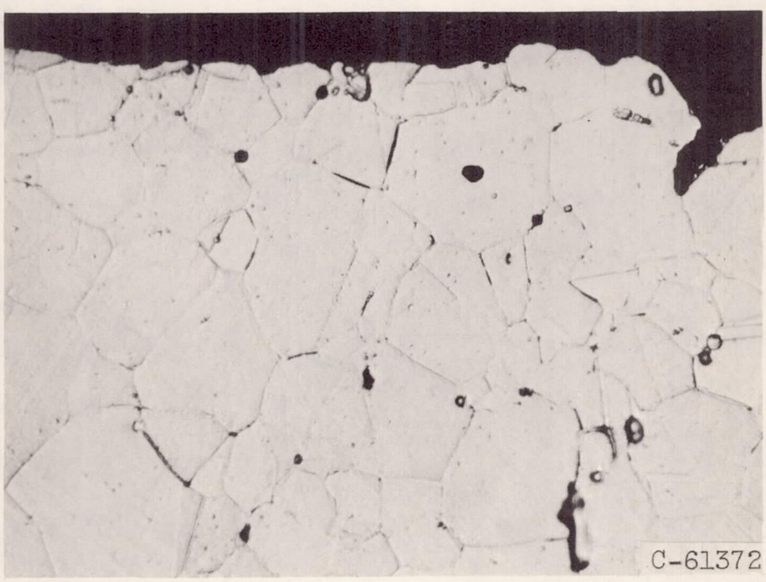
X100

Internal surface



External surface

X500

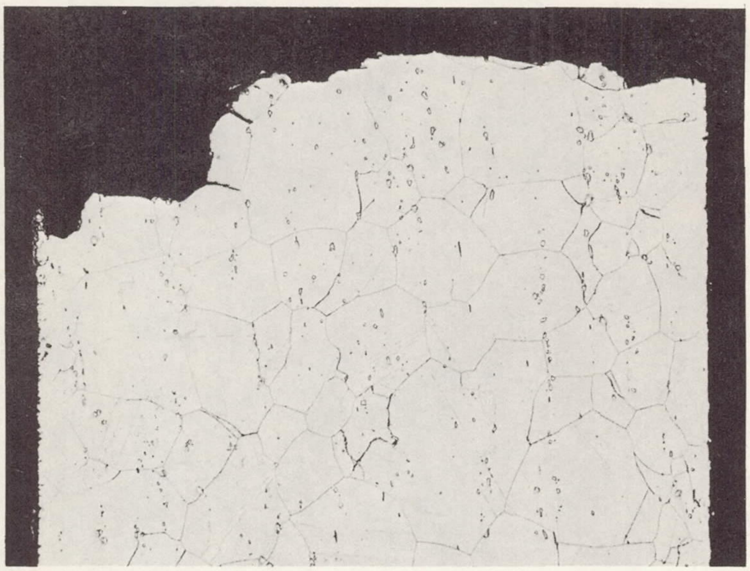


(a) A-286; internal surface exposed to air; life, 22.6×10^6 cycles (191.2 hr).

Figure 5. - Transgranular fractures typical of failures encountered in fatigue tests with both air and hydrogen.

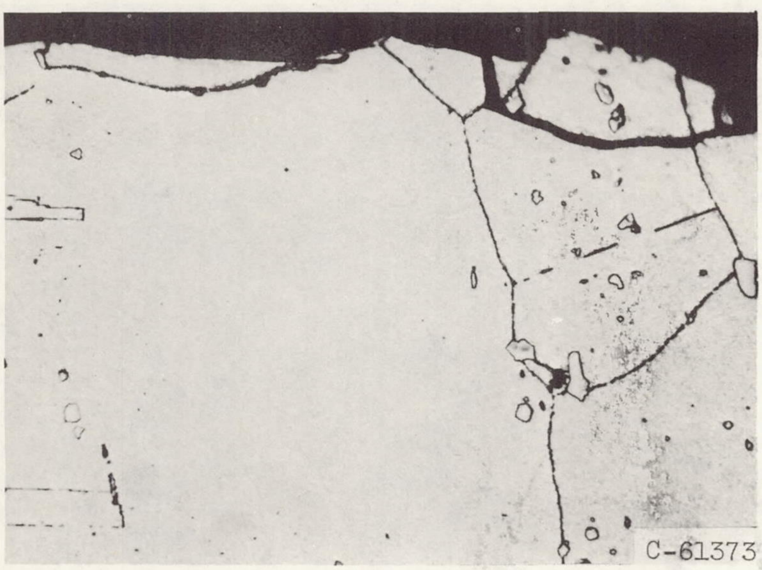
X100

External surface



Internal surface

X500

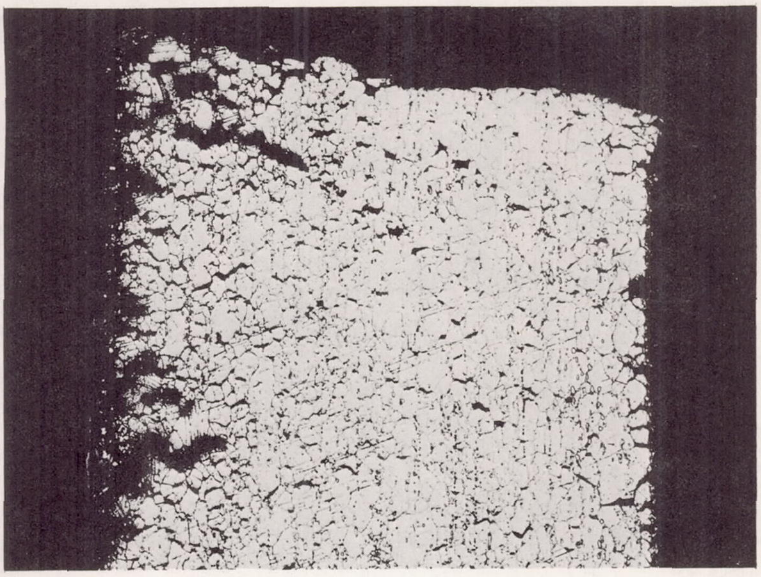


(b) Inconel 700; internal surface exposed to hydrogen; life, 89.0×10^{6} cycles (750.4 hr).

Figure 5. - Continued. Transgranular fractures typical of failures encountered in fatigue tests with both air and hydrogen.

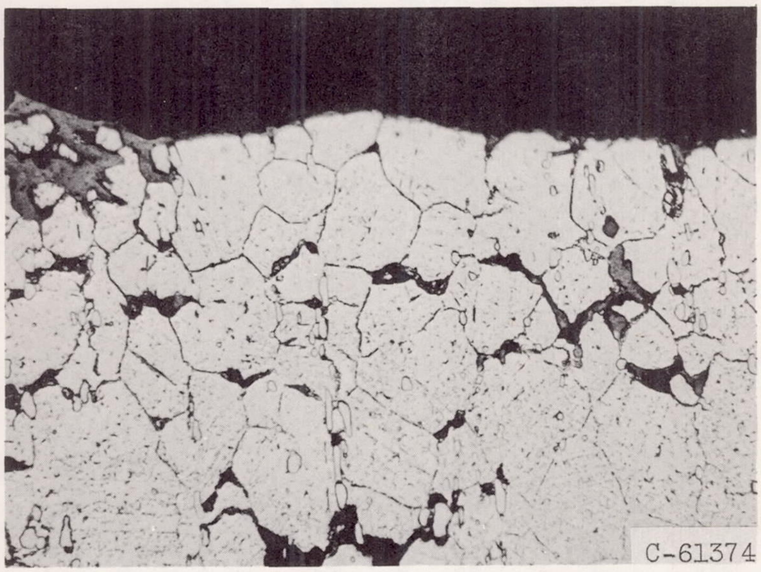
X100

External surface



Internal surface

X500

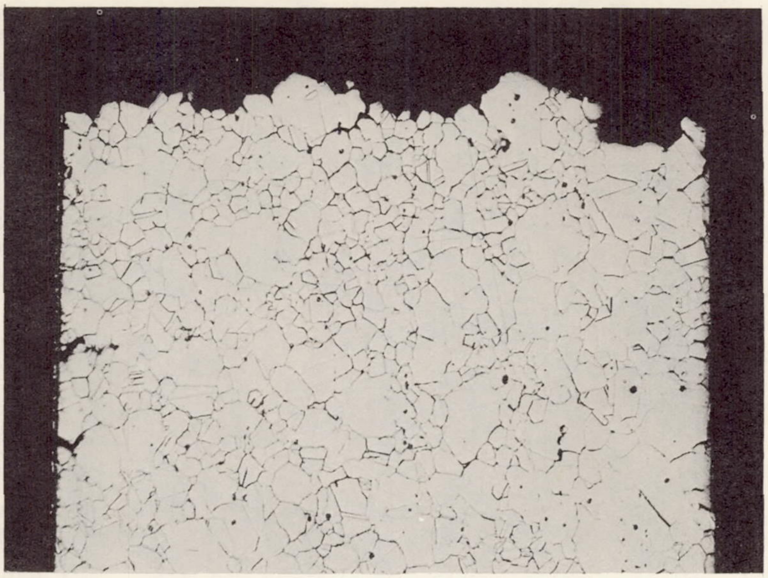


(c) S-816; internal surface exposed to air; life, 27.5×10^6 cycles (232.9 hr).

Figure 5. - Concluded. Transgranular fractures typical of failures encountered in fatigue tests with both air and hydrogen

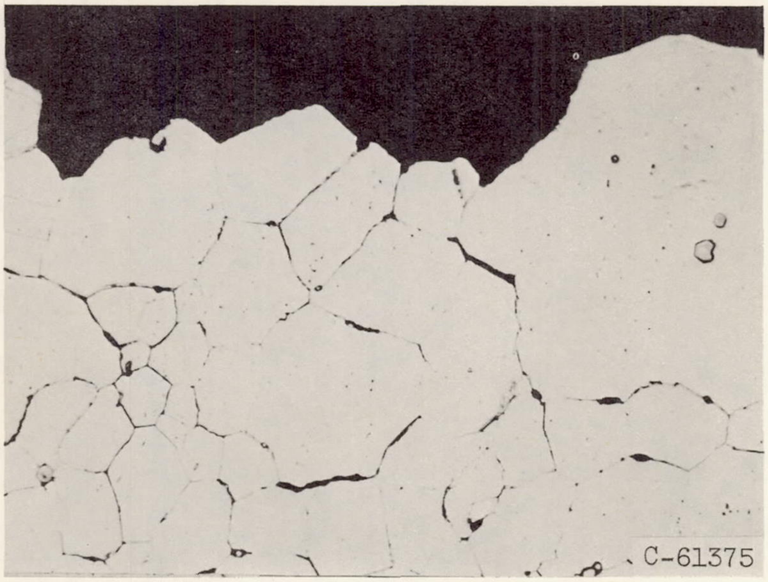
X100

Internal surface



External surface

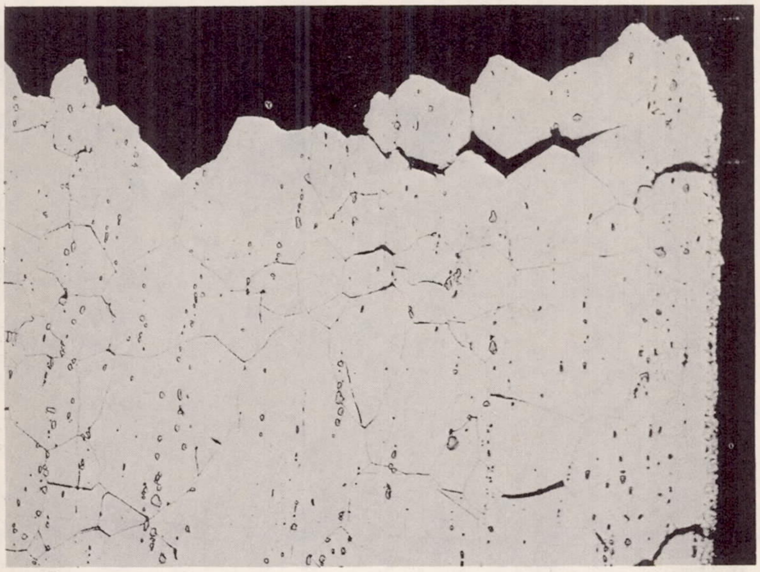
X500



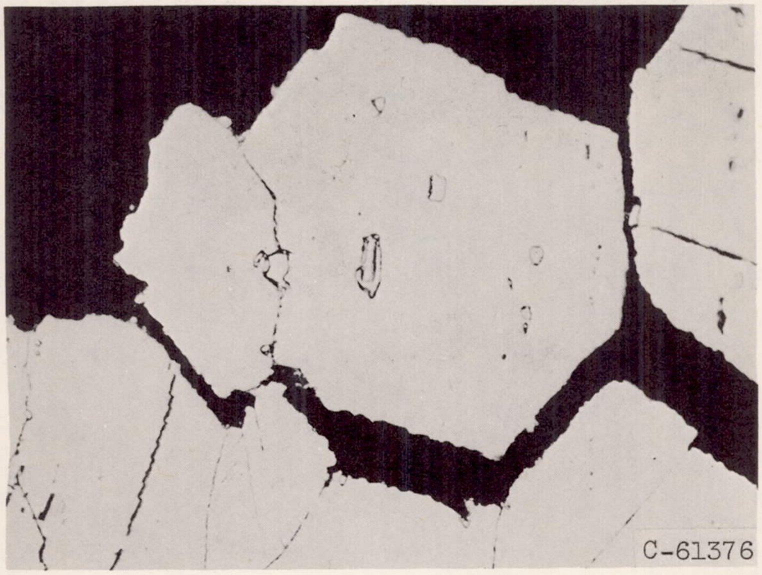
(a) A-286; internal surface exposed to air; life, 316.8 hours.

Figure 6. - Intergranular fractures typical of failures encountered in stress-rupture tests with both air and hydrogen.

X100



X500

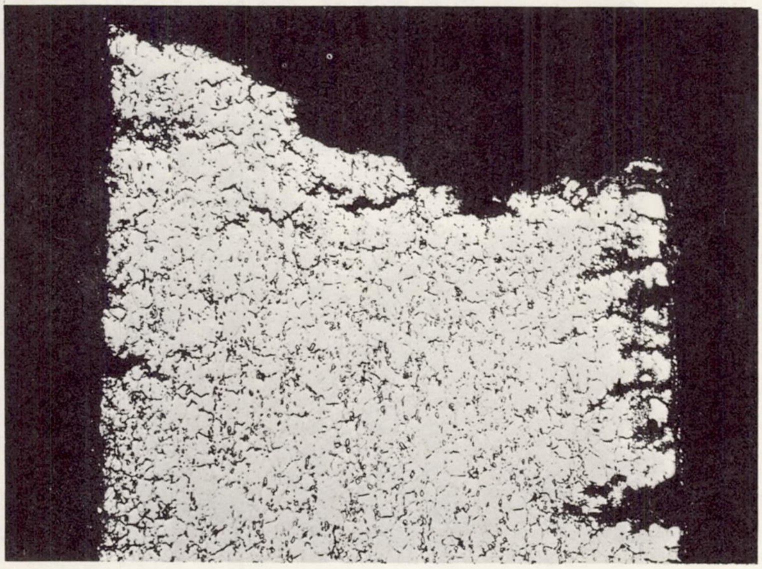


(b) Inconel 700; internal surface exposed to hydrogen; life, 198.3 hours.

Figure 6. - Continued. Intergranular fractures typical of failures encountered in stress-rupture tests with both air and hydrogen.

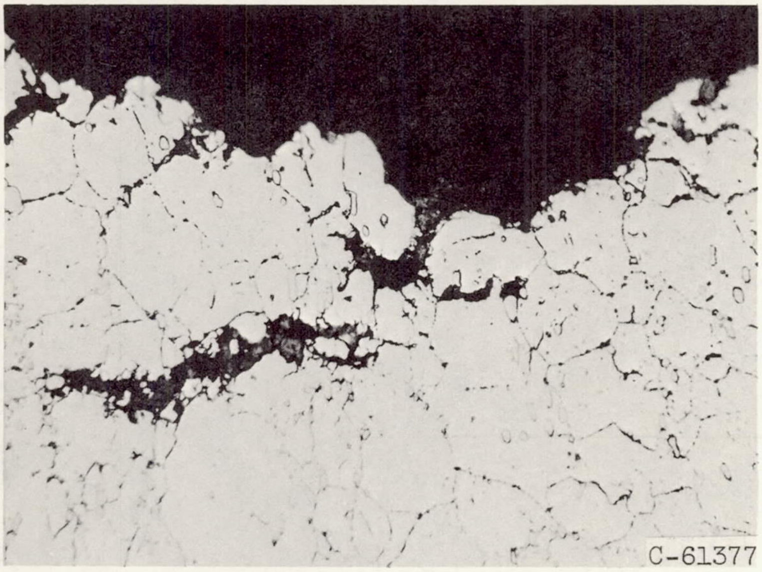
X100

Internal surface



External surface

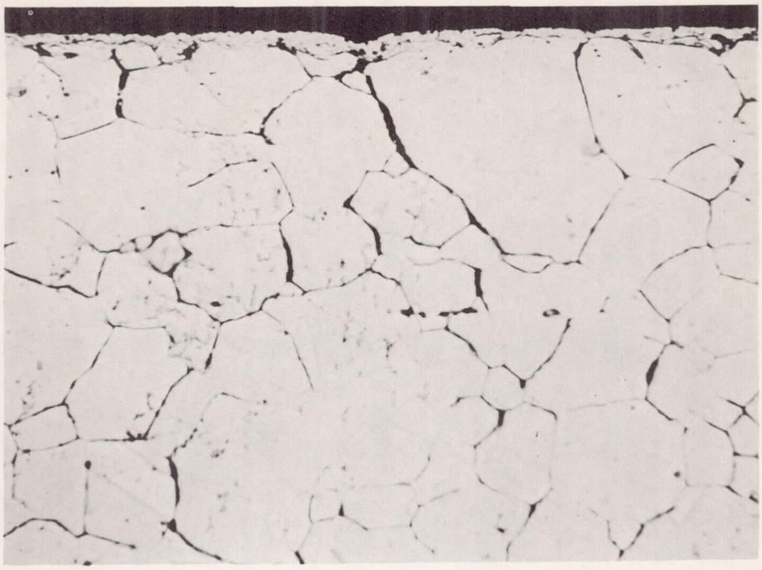
X500



(c) S-816; internal surface exposed to air; life, 166.6 hours.

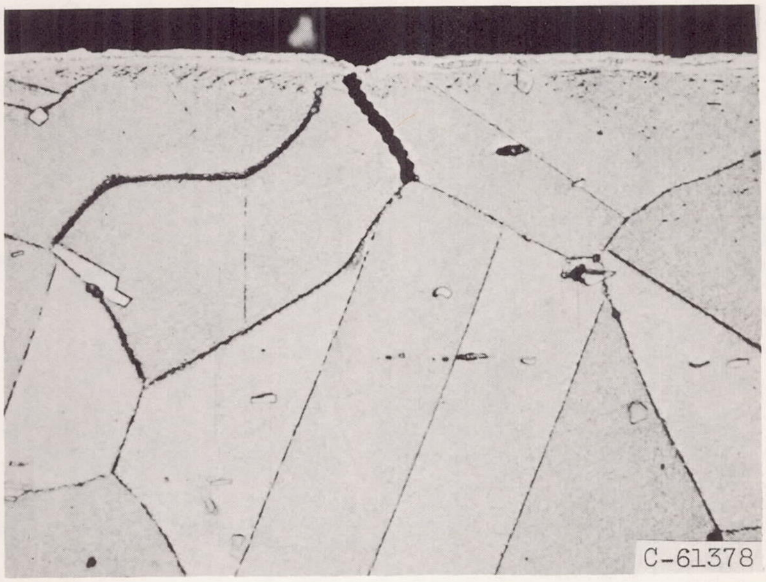
Figure 6. - Concluded. Intergranular fractures typical of failures encountered in stress-rupture tests with both air and hydrogen.

X500



(a) A-286; stress-rupture test; life, 280 hours.

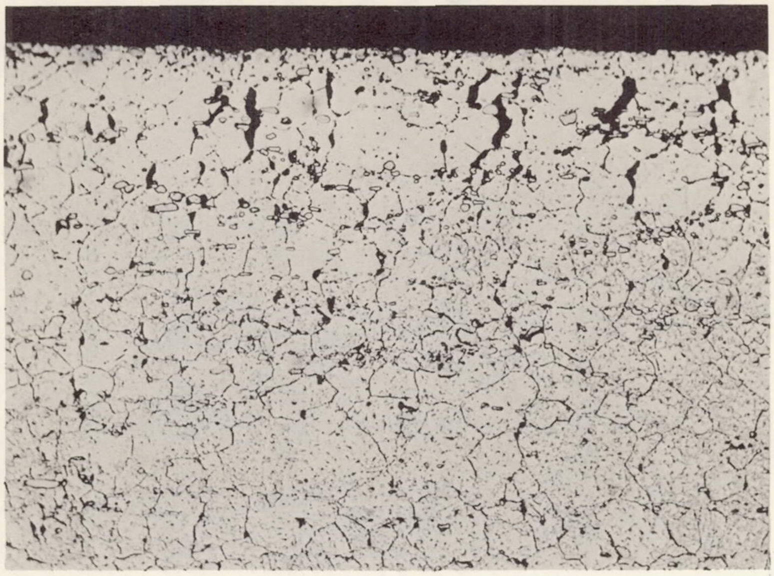
X500



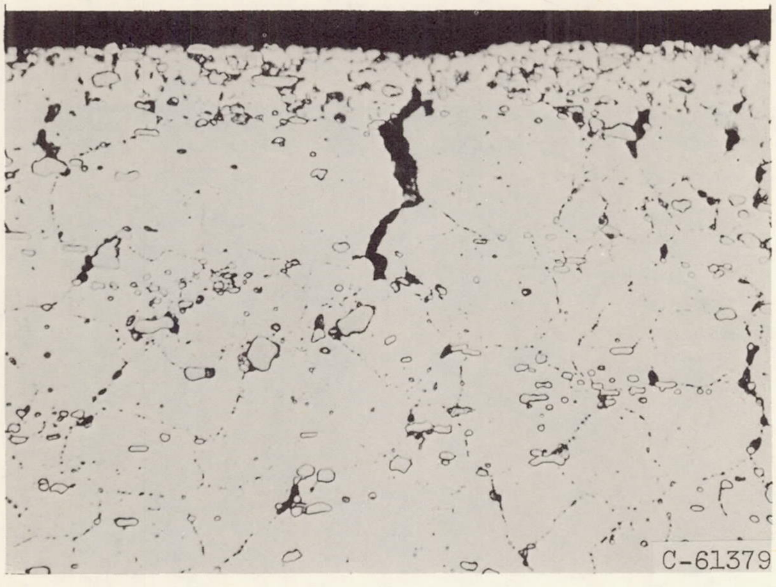
(b) Inconel 700; stress-rupture test; life, 198.3 hours.

Figure 7. - Area near region of failure of typical specimens showing internal surface after exposure to hydrogen.

X250

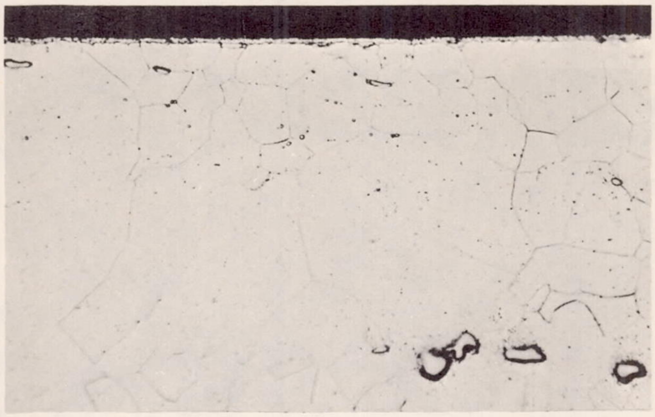


X500

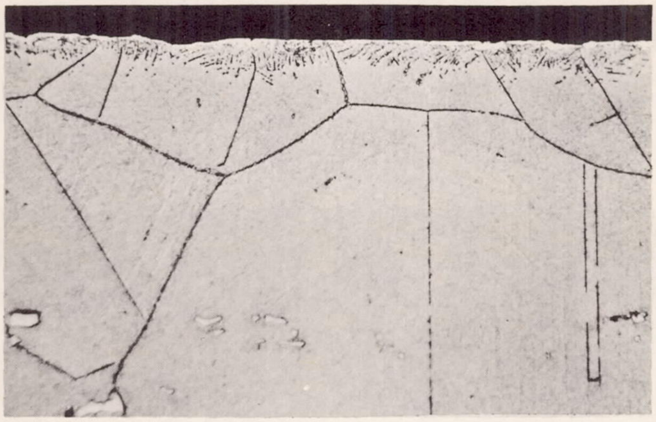


(c) S-816; fatigue test; life, 42×10^6 cycles (357.1 hr).

Figure 7. - Concluded. Area near region of failure of typical specimens showing internal surface after exposure to hydrogen.



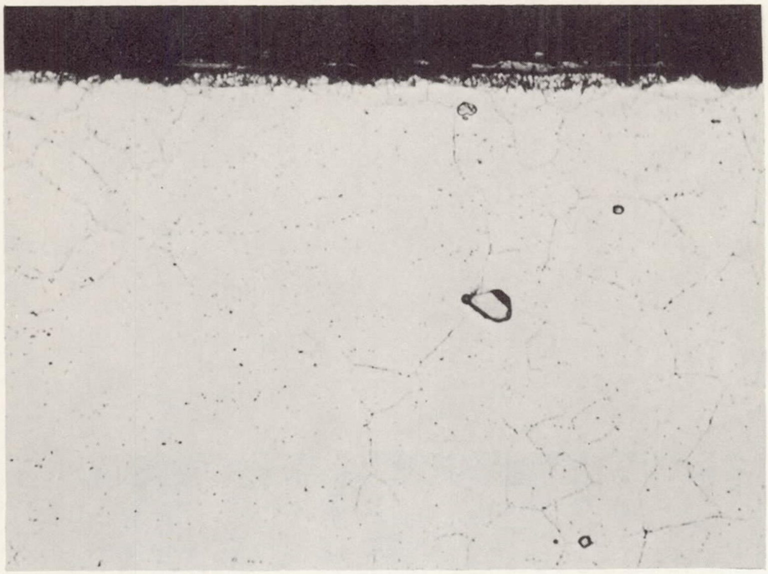
(a) A-286; stress-rupture test; life, 246.6 hours.



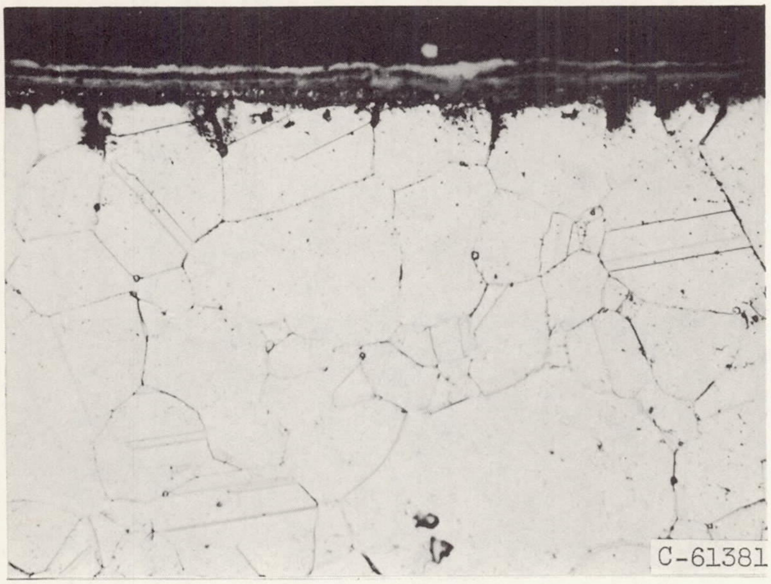
(b) Inconel 700; fatigue test; life, 49.0×10^6 cycles (411.1 hr).

(c) S-816; fatigue test; life, 31.0×10^6 cycles (262.2 hr).

Figure 8. - Area some distance from region of failure of typical specimens showing internal surfaces after exposure to hydrogen. X500.



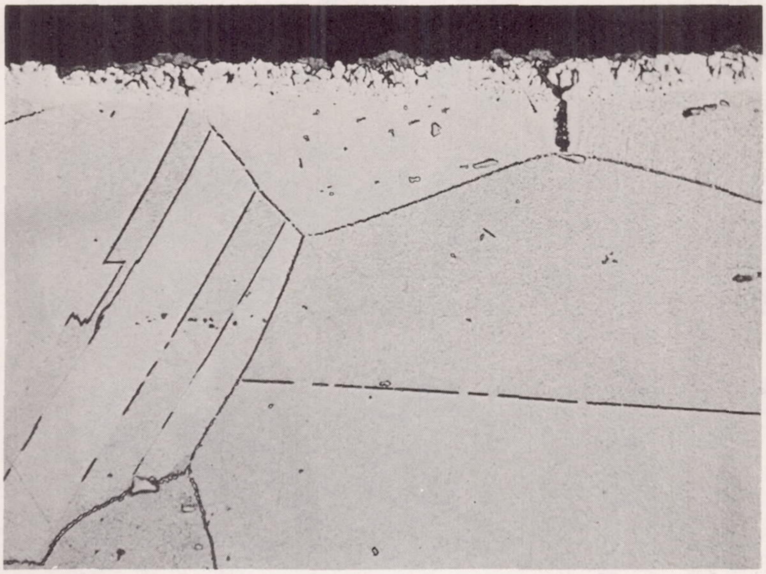
Internal surface



External surface

(a) A-286; fatigue test; life, 33.6×10^6 cycles (284.2 hr).

Figure 9. - Typical specimens showing both internal and external surfaces in region of failure. Internal surface exposed to dried air; external surface exposed to relatively humid air. X500.

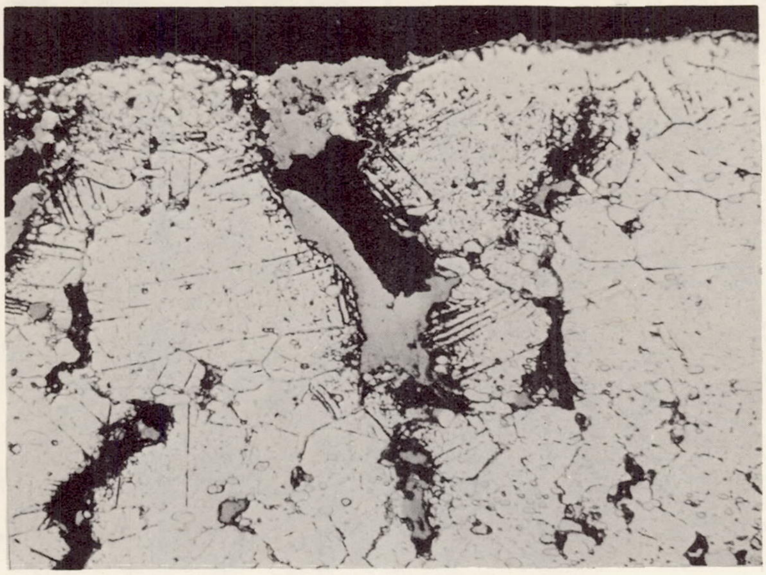


Internal surface

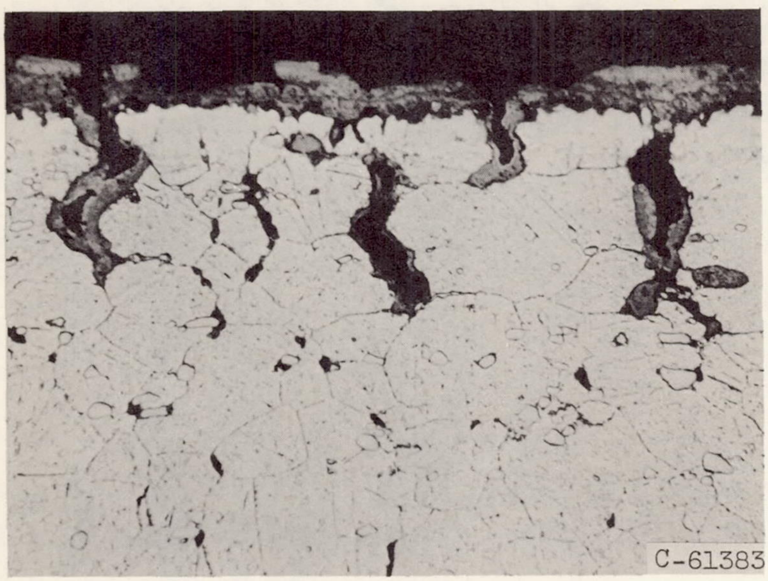
External surface

(b) Inconel 700; fatigue test; life, 83.4×10^6 cycles (705.5 hr).

Figure 9. - Continued. Typical specimens showing both internal and external surfaces in region of failure. Internal surface exposed to dried air; external surface exposed to relatively humid air. X500.



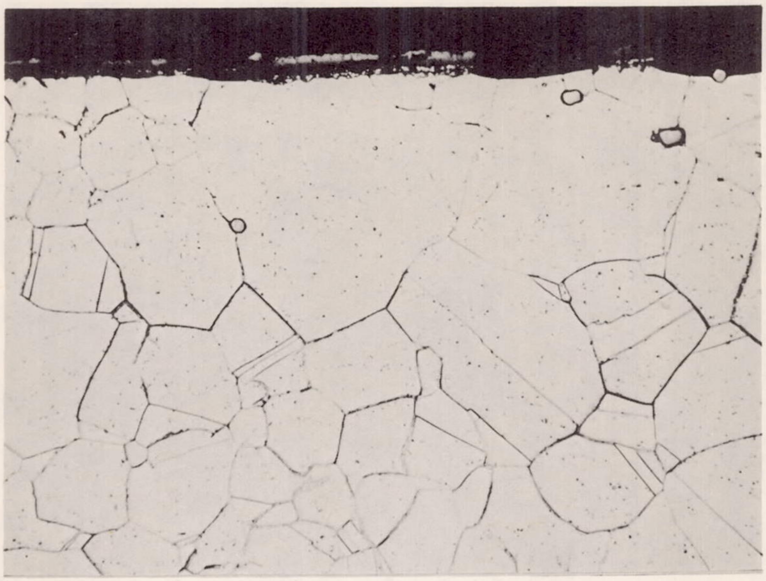
Internal surface



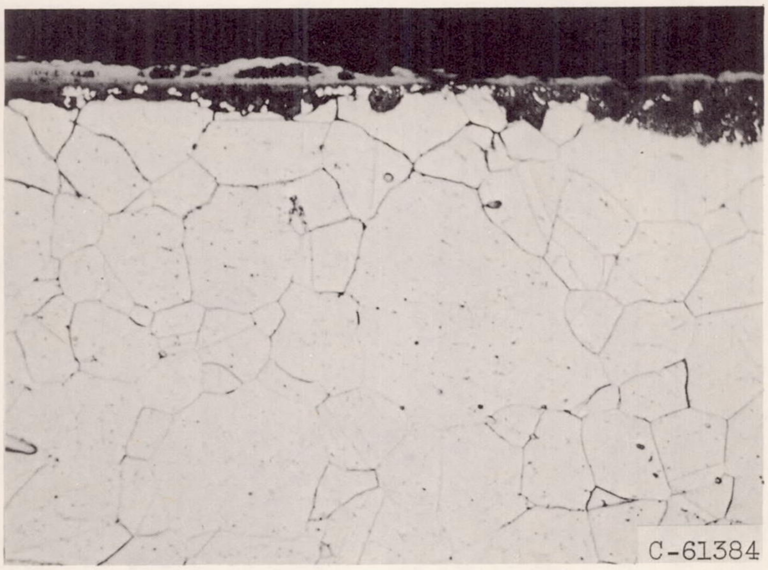
External surface

(c) S-816; stress-rupture test; life, 232.8 hours.

Figure 9. - Concluded. Typical specimens showing both internal and external surfaces in region of failure. Internal surface exposed to dried air; external surface exposed to relatively humid air. X500.



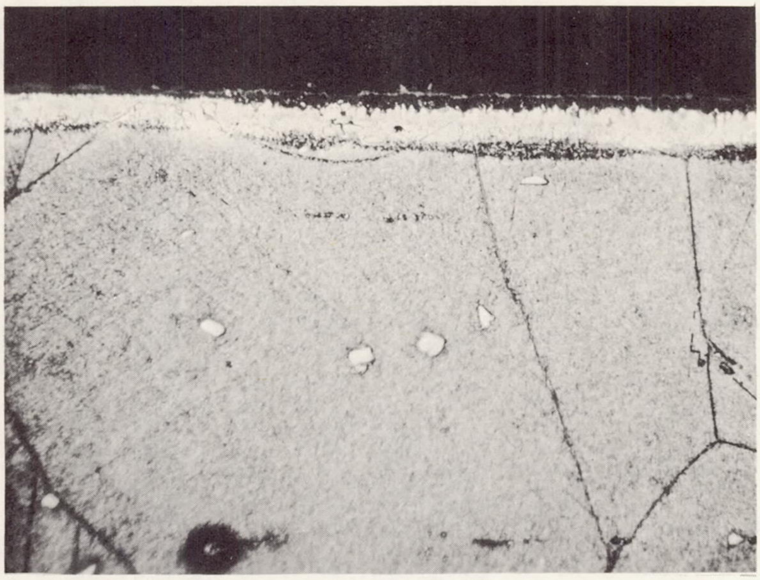
Internal surface



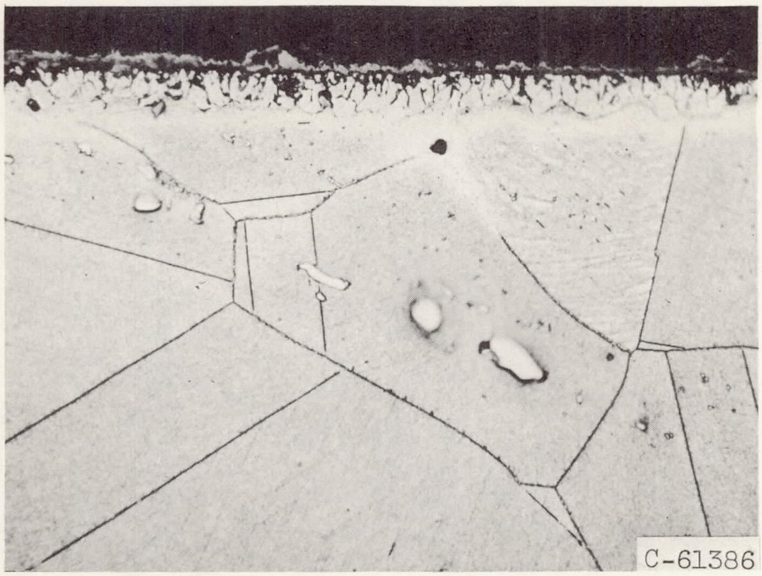
External surface

(a) A-286; fatigue test; life, 33.6×10^6 cycles (284.2 hr).

Figure 10. - Typical specimens showing both internal and external surfaces in area some distance from region of failure. Internal surface exposed to dried air; external surface exposed to relatively humid air. X500.



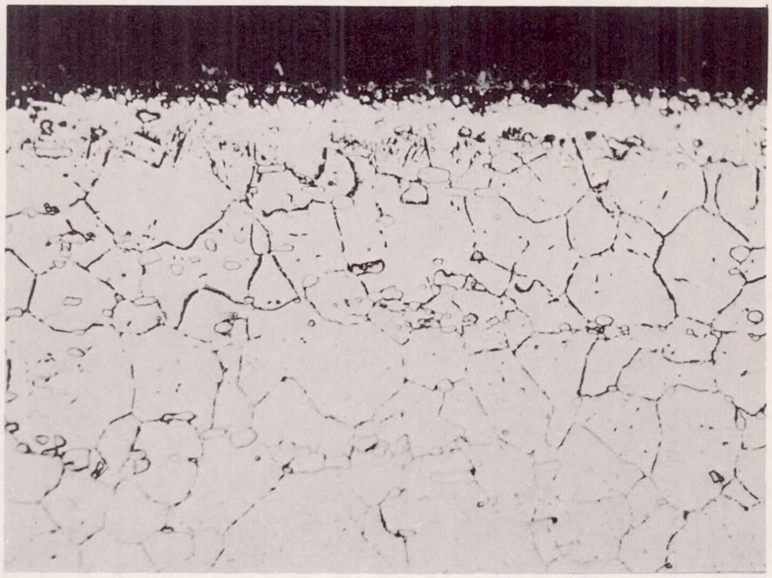
Internal surface



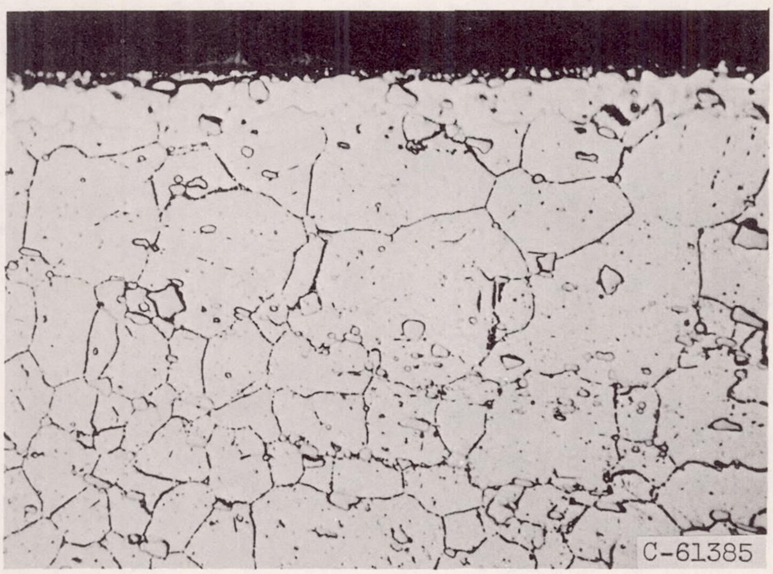
External surface

(b) Inconel 700; fatigue test; life, 47.4×10^6 cycles (401.6 hr).

Figure 10. - Continued. Typical specimens showing both internal and external surfaces in area some distance from region of failure. Internal surface exposed to dried air; external surface exposed to relatively humid air. X500.



Internal surface



External surface

(c) S-816; fatigue test; life, 31.2×10^6 cycles (263.8 hr).

Figure 10. - Concluded. Typical specimens showing both internal and external surfaces in area some distance from region of failure. Internal surface exposed to dried air; external surface exposed to relatively humid air. X500.